Journal of Machine Engineering, Vol. 9, No. 1, 2009

*energy and carbon footprint;
machining; sustainable manufacturing.*

M. F. RAJEMI[1]
P. T. MATIVENGA[1]
S. I. JAFFERY[1]

ENERGY AND CARBON FOOTPRINT ANALYSIS FOR MACHINING TITANIUM Ti-6Al-4V ALLOY

Titanium alloys are increasingly being used in manufacturing especially in aerospace industries. The environmental impact of using this material is rarely discussed especially with regards to energy consumption and its contribution to carbon emissions. The poor machinability of titanium leads to lower material removal rate and longer machining time. Coupled with high carbon footprints encountered, in extracting this material from ore, it is clear that the environmental impact of using this material needs to be optimised. In the research reported here, cutting tests were undertaken on a lathe and milling machine using unified cutting conditions. The associated energy and carbon footprints were analysed and discussed with emphasis on high speed machining. The paper clearly shows the impact of process choice and cutting speed on environmental footprints as a key performance measure in sustainable manufacturing.

1. INTRODUCTION

1.1. INDUSTRY AND THE ENVIRONMENT

It is now generally accepted that the world is facing increasing risks of serious, irreversible impact from climate change associated with business as usual paths for emissions. In 2006, a UK intergovernmental panel named the STERN REVIEW presented a study on the economics of climate change. The review pointed out that in the year 2000, 24% and 14 % of CO_2 emissions came from power generation and industry respectively ("STERN REVIEW: The Economics of Climate Change", 2006). Thus developing cleaner power sources as well as reducing CO_2 emissions from industrial activities are essential requirements in mitigating the impact of climate change. Additionally, the world simultaneously faces a scarcity and diminishing of resources. For manufacturing managers the challenge is how to enhance industrial productivity and at the same time reduce the negative effects of production operations on the environment.

On 11 December 1997, the Kyoto Protocol ("Kyoto Protocol", 1997) which involved 182 parties including 36 developed countries and the European Union agreed on reducing

[1] E-mail address : Mohamadfarizal.Rajemi@postgrad.manchester.ac.uk

5. CONCLUSIONS

In this paper we presented the idea of project portfolio cash flow management supported by IDSS systems. The IDSS is able to assist decision makers in major capital investments such as the introduction of new products, which requires cash flow information over the life of the project. The investment profitability estimation depends on cash flow estimations, which are generally uncertain. Many cash flow elements (such as demand) are subject to substantial uncertainties. The proposed solution enables real time tracking of project cash flows. It makes the ENPV calculation for alternative assessments and risk calculation possible. The case study helps to understand how the proposed methodology could be used. Yet there are several limitations, such as indifference to the strategy of the company (i.e., a project could have worse expected NPV but it could bring more value in the long-term), the proposed method is still deterministic and it does not include in calculations the uncertainty in the future cash flows. Also it is practically difficult to track cash flow sequence of the different projects and the main constraint that all projects should be performed simultaneously.

ACKNOWLEDGEMENTS

Hereby we would like to thank the Estonian Science Foundation for Finance Scheme T213B that enabled us to carry out this work. Authors also thank Kaja Olek for the interesting topic and discussions.

REFERENCES

[1] BAROUM S.M., PATTERSON J.H., *The development of cash flow weight procedures for maximizing the net present value of a project.* Journal of Operations Management, Volume 14, Number 3, September 1996.

[2] KAKA A. P., PRICE A. D. F., *Modeling standard cost commitment curves for contractors' cash flow forecasting* Construction Management and Economics, Volume 11, Issue 4 July 1993.

[3] BARBOSAP., PIMENTEL P., *A linear programming model for cash flow management in the Brazilian construction industry.* Construction Management and Economics (2001) 19, 2001, 469-479.

[4] KRAMARENKO S., SHEVTSHENKO E., KARAULOVA T., WANG Y., *Decision Analysis in Project Management Process.* Journal of the Machine Engineering, Wroclaw, Poland v.8, No.1, 2008.

[5] ENGWALL M., JERBRANT A., *The resource allocation syndrome: the prime challenge of multi-project management.*2003 International Journal of Project Management, Volume 21, Issue 6, 2003.

[6] HENDRICKSON C., *Project Management For Construction Fundamental Concepts For Owners*, Engineers, Architects And Builders Prentice Hall, ISBN 0-13-731266-0, 1989.

[7] PMBOK., *A Guide to the Project Management Body of Knowledge Third Edition* an American National Standard ANSI/PMI 99-001-2004.

[8] CORNELIS A. LOS., *Measuring financial cash flow and term structure dynamics*,2001.

[9] FLAIG J., *Improving Project Selection Using Expected Net Present Value Analysis* (2005). Quality Engineering, Taylor & Francis Inc. ISSN: 0898-2112.

[10] BLANCHARD B. S., FABRYCKY W. J., Systems Engineering and Analysis. Englewood Cliffs, NJ: Prentice-Hall, 1990.

[11] BRIGHAM E., GAPENSKI L., EHRHARDT M., *Financial management: theory and practice, 9th Ed. The Dryden Press*,1999.

[12] MUNSON B., YOUNG D., OKIISHI T., *Fundamentals of fluid mechanics, 3rd Ed.,* Wiley,ISBN 0471170240, 1998.

greenhouse gases (GHG) to targets set for each country. Never-the-less the operational strategies needed to reduce the GHG, are still unclear especially for manufacturing industries. In the United Kingdom the industrial sector consumes the highest amount of electrical energy compared to other users. High demand for energy increases environmental footprints since emissions such as carbon dioxide are traceable to the process of power generation. Thus industrial communities can cut the carbon emission penalty for their electrical energy sources by switching to clear power generation sources such as nuclear and hydro electric. However, the time frame and investment required for setting up an alternative electrical energy generation source is long and expensive respectively. Reducing energy demand by the industrial consumer presents immediate action that requires urgent attention. This is particularly critical because it takes a long time to de-carbonise already polluted atmosphere. Apart from climate change the escalating cost of energy requires that manufactures reduce energy consumption in order to cut operating costs.

In an attempt to the analyse the environmental problem, Gutowski (Gutowski, 2007) disaggregated carbon emissions in terms of components as shown in Equation 1.

$$Carbon = Pop \times \frac{GDP}{Pop} \times \frac{Energy}{GDP} \times \frac{Carbon}{Energy} \tag{1}$$

It is generally agreed that reducing the world population to cut carbon emissions is a very unlikely strategy and beyond the scope of manufacturing engineers. In production engineering, it is conceivable, to promote a higher gross domestic product (GDP) while reducing energy consumption. The carbon intensity of energy can be tackled in the long term by investing in cleaner sources of energy.

The carbon emissions can be calculated using a Carbon Emission Signature (CES) (Jeswiet & Kara, 2008). This factor expresses the amount of CO_2 in kilograms, emitted per giga Joule of energy generated in a power station. Thus, the factor depends on the source of electrical power and varies depending on the mix of power stations types. In literature the coefficient used for calculating carbon emission was based on data from Canada and Australia (Jeswiet & Kara, 2008). In the United Kingdom, Department for Environment, Food and Rural Affairs (DEFRA) guidelines are usually used to calculate carbon emissions ("Carbon Trust Methodologies: DEFRA Guidelines for measuring and reporting of emissions in the UK emissions trading scheme", 2003). Accurate analysis of CES requires the source of generation for the electricity to be indentified. In order to ease this problem, the climate Change Levy Negotiated Agreements and the UK Emissions Trading Scheme (ETS) use an average carbon intensity factor for electricity of 0.43 $kgCO_2/kWh$ ("Guidelines to DEFRA's GHG Conversion Factors for Company Reporting", 2007).

1.2. ENERGY FOOTPRINTS IN MACHINING

Mechanical machining is one of the widely used processes in industry for manufacturing of discrete parts. Titanium alloys are now finding increasing use in aerospace manufacturing as well as medical devices. This paper focuses on the electrical power and hence energy requirements for machining titanium alloy. From literature, it was suggested that the energy required for the material removal processes can be quite small compared with the total energy for the machine tool operation (Gutowski et al, 2006). Additionally, the energy footprint for primary processes is usually higher than that for secondary shaping processes (Gutowski, 2007). For example the carbon footprint for extracting a range of workpiece materials from their natural ore is shown in Fig. 1 as generated from the Cambridge Engineering Selector Software ("Cambridge Engineering Selector (CES)", 2005). The data shows that relative to steel, aluminium, cast iron or brass, the extraction of titanium alloys is associated with the highest carbon footprint. In extracting one kg of titanium alloy, 55kg of carbon is produced. Such considerations are seldom taken into account when selecting a material for a particular application. This, emphasis the need for a holistic view of the life cycle of a product if the greatest strides in cutting carbon emissions are to be realised.

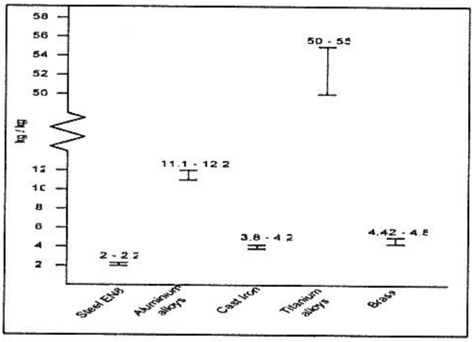

Fig. 1. Carbon footprint per kg of raw material produced ("Cambridge Engineering Selector (CES)", 2005)

Notwithstanding this factor, for manufacturing companies the raw material inputs are usually defined by the customer and sustainable innovations thus relate to improvements in the secondary production processes. The energy requirement for machining a material through mechanical cutting depends on the specific energy in cutting operations. Representative specific energy values for machining a range of materials are available in literature (Kalpakjian & Schmid, 2006). The values to be applied depend on the combination of tooling and workpiece material/grades used. Following on earlier work (Gutowski et al, 2006), the electrical power requirement, P, for machining can be calculated from Equation 2.

$$P = P_0 + k\dot{v} \tag{2}$$

Where, P_o is the idle power (or power consumption for machine tool that is running but not actually cutting) in kW, k is the specific energy requirements in cutting operations, in Ws/mm^3 and $\dot{v}$ is the material removal rate (MRR), in mm^{3}s^{-1}. From equation 2 the total power for machining can be identified as the idle power P_o and the machining power $(k\dot{v})$.

The idle power is the power required for equipment features that support the machine. For example the power to start up the computer and fans, the motor and the coolant pump. The machining power, P, for a machine tool using a three phase motor is calculated using equation 3.

$$P = V \cdot I \cdot \sqrt{3} \tag{3}$$

Where V, is the voltage and I is the Current. The energy required for machining process, E, can be deduced from converting the power equation 2 into an energy equation 4.

$$E = (P_0 + k\dot{v})t \tag{4}$$

Where, t is the time in seconds taken for machining, and the other symbols retain their usual meaning. In the manufacture of a product through machining, the carbon footprint of the product can be calculated from the carbon footprint for extracting the raw material, the carbon intensity of energy used in executing the process and any other process emissions (Dahmus & Gutowski, 2004).

Earlier work reported by the authors showed that the lathe machine tool was the significant consumer of energy compared to the actual cutting process (Rajemi & Mativenga, 2008). The motivation for this work was to explore how the energy and carbon footprint of a product made from a popular titanium aerospace alloy would vary for different cutting conditions and types of machining process. This information is essential in planning for manufacture of sustainable products.

2. RESEARCH METHOD

A titanium 6Al-4V alloy block (85 mm long and 42 mm width) was end face milled on a CNC TAKISAWA milling machine (Fig. 2). Table 1 shows the range of cutting conditions used for the tests.

Table 1. Cutting conditions for the milling tests

Cutting variable	Range tested
Cutting speed, V_c (m/min)	30 - 80
Spindle speed, N (RPM)	298 – 796
Feedrate, f_z (mm/tooth)	0.15
Depth of cut, a_p (mm)	1
Width of cut, a_e (mm)	4
Tool diameter, D (mm)	32
Insert type (TPMN160308 H13A)	Uncoated carbide
Numbers of inserts on tool holder	1
Workpiece material	Titanium 6Al-4V
Composition of workpiece material	89.37% Ti, 6% Al, 4% V, 0.08%C, 0.3% Fe, 0.2 % O_2, 0.05% N

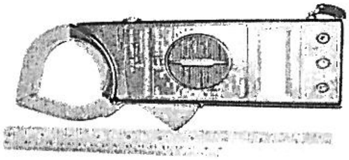

Fig. 2. DT-266 Digital Clamp Meter

As shown in Table 1, in this part of the research, the depth of cut was kept constant at 1 mm but the feedrate and cutting speed were varied. In total 15 different sets of cutting conditions were tested. To standardise the cutting tests and enable comparison between different cutting conditions, a general purpose uncoated (TPMN160308 H13A) carbide insert was used. The cutting condition used were within the range of cutting speeds reported in literature (Jaffery & Mativenga, 2008). The final comparison of the power and hence energy requirements was done at the recommended/optimum cutting condition for the tooling and workpiece material. After starting the machine, current consumption for the idle or non cutting machine was measured. The current was then recorded for the different cutting conditions.

The electrical power consumption was measured using a DT-266 digital clamp meter (Fig. 2). The clamp meter was clamped on one of the three live wires supplying electricity to the three phase motor of the CNC TAKISAWA milling machine. The clamp meter rely on the hall effect to measure the current flow through the life wire (Kardonowy & David, 2002).

The current drawn was also measured for actions such as rapid movement of tool to original location (machine jog). In order to reduce the power consumption, dry cutting was adapted.

3. RESULTS AND DISCUSSIONS

To evaluate the specific energy for the material it was necessary to calculate the specific power for a range of material removal rates. Fig. 3 shows the variation of power consumption with material removal rate (MRR). The power measured is the actual cutting power (net power for machining). The idle power (i.e. non-cutting operation) and other activity that involves the consumption of power such as positioning the tool, rapid movement to original position (in this case is axes jog) and rotating spindle without cutting (idle condition with spindle turning) is not considered for generating this graph.

From Fig. 3 the specific power requirement for machining the titanium alloy “k” is 3.7 $Wsmm^{-3}$. This value lies in the range of 2-5 $Wsmm^{-3}$ as reported by Kalpakjian & Schmid (Kalpakjian & Schmid, 2006). The power value was then calculated for different cutting speeds. Fig. 4 shows a comparison between the total power consumption and cutting power.

The constant difference between the total power and cutting power as shown in Fig. 4 is an indication of the non cutting power (power for operating the machine at zero loads).

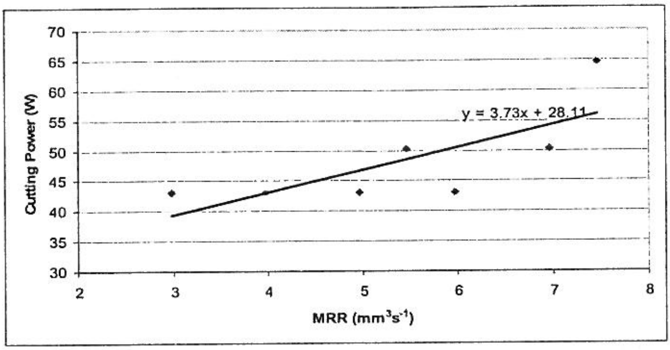

Fig. 3. Variation of power consumed with material removal rate

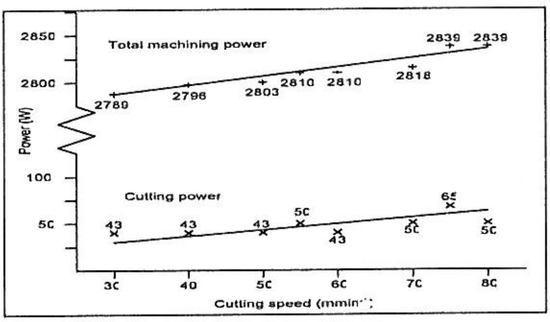

Fig. 4. Power consumption on a CNC TAKISAWA milling machine

Further analysis of the cutting process was undertaken at the recommended set of cutting conditions of a cutting speed of 75 m/min, feed of 0.15 mm/tooth and depth of cut of 1 mm. (Jaffery & Mativenga, 2008). Fig. 6 shows the power distribution for this particular cutting condition.

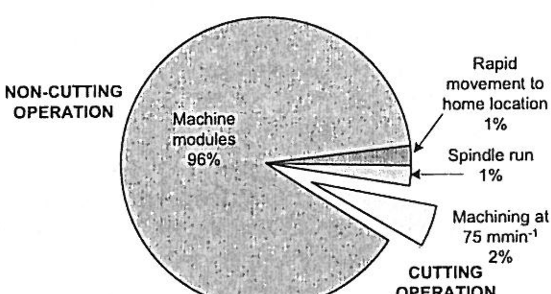

Fig. 5. The power distribution on a CNC TAKISAWA milling machine

The power distribution can be divided into two groups. The first group is the power for non-cutting operations. The non-cutting operation includes the power required to turn on the machine modules (for example computer and fans, hydraulic pump etc.), rapid movement to home location (axes jog) and running the spindle without cutting (idle condition with spindle on). For this research, this value consumes most of the power supply for the machining process, i.e. 98%. Only 2% of the energy is used for the actual cutting process itself. Dahmus and Gutowski (Dahmus & Gutowski, 2004) found that the share of energy for machining process varied from 0 up to 48.1% depending on the load of machining. Since in this research, the machining process is an end milling process, the amount of energy used is less compared to machining a slot as in Kardonowy (Kardonowy & David, 2002). The results also show an interesting fact, that the milling the machine consumes a bulk of the energy when it is in an idle condition. Thus turning on such a machine has major impact on the energy footprint for the process. From energy footprint consideration such machines should not be left in an idle position for a considerable amount of time.

The study also compared the energy profile for a milling machine to that of a lathe machine for similar material removal (cutting speed of 75 m/min, feed rate is 0.15 mm/rev and depth of cut 1 mm). The data for the lathe machine was published before (Rajemi & Mativenga, 2008). Fig 6 clearly shows that the milling machine uses less energy compared to lathe operations. In the lathe operation, the spindle holds the workpiece; therefore a bigger workpiece will demand more power to rotate. In milling, the spindle holds typically a relatively small tool; hence it reduces the power required by the motor. Compared to other operations, positioning the tool consumes negligible power.

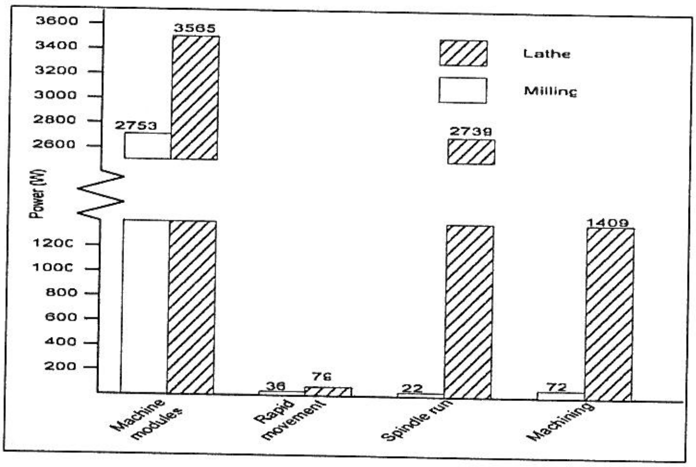

Fig. 6. Comparison between a CNC TAKISAWA milling machine and MHP lathe for similar cutting conditions

Data for both machining centres shows that machine modules or idle power dominates the machining process. Comparing power utilization for both machining processes, it is clear that lathe machining processes has better power utilization whereby almost 18%

of energy is being used for actual cutting operation whereas for milling only 2% of total power consumption is used for cutting process.

The energy to remove 10 cm^3 of Ti-6Al-4V for both machines was estimated as shown in Table 2. Table 2 clearly shows that energy to remove 10 cm^3 of Ti-6Al-4V for milling is higher than the lathe machining process. The reason for this result lies in the fact that the material removal rate in milling is lower. This factor leads to a higher time taken to remove 10 cm^3 of Ti-6Al-4V in milling (compared to lathe) which results in higher energy consumption. The lathe has a higher power demand but better power distribution and less energy to remove 10 cm^3 of Ti-6Al-4V. The "spindle factor" affects the power distribution and total energy consumption in machining. Another factor that needs a serious consideration is the material removal rate. As material removal rate increase the time taken to remove a specific volume of material reduces and hence energy consumption for the whole machining process also goes down.

Table 2. Cutting conditions and energy to remove 10 cm^3 of Ti-6Al-4V

	Takisawa Miller	MHP Lathe
Feed	0.15 mm/tooth	0.15 mm/rev
Depth of cut	1 mm	1 mm
Cutting speed	75 m/min	75 m/min
Spindle speed	746 rpm	411 rpm
Material removal rate	447 mm^3/min	11059 mm^3/min
Time taken to remove 10 cm^3	22.3 min	0.9 min
Energy for actual cutting	0.09 MJ	0.08 MJ
Total energy for machining	**3.81 MJ**	**0.42 MJ**

The study further assessed the effects of higher cutting speeds on energy consumption. The energy required was calculated by considering the time to remove 10 cm^3 of workpiece material as well as the power consumption. Additionally, the carbon dioxide associated with

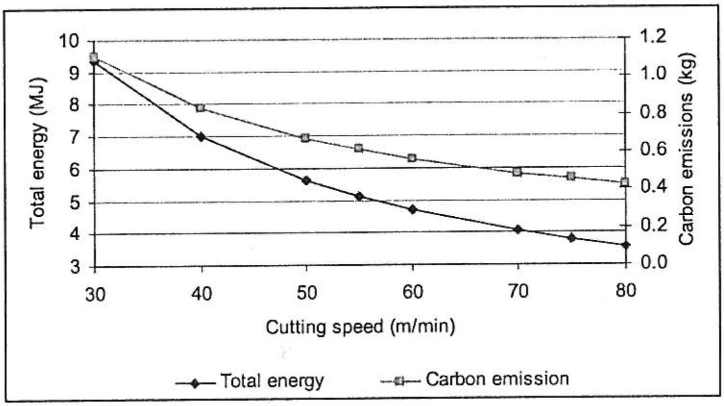

Fig. 7. Total energy required for a Takisawa Milling Machine to remove 10 cm^3 of titanium alloy and carbon emissions

the energy was calculated by taking a fuel emission factor of 0.43 $kgCO_2/kWh$ for the energy source ("Carbon Trust Methodologies: DEFRA Guidelines for measuring and reporting of emissions in the UK emissions trading scheme", 2003). The CO_2 emission was calculated excluding the amount of CO_2 emitted in producing 10 cm^3 raw material of titanium alloy in order to show differences in machining process.

It can be seen in Fig. 7 that the total energy to remove 10 cm^3 of titanium alloy is reduced as the cutting speed increases. Carbon emissions are reduced proportionally as total energy for machining reduces. This information shows that cutting conditions should be evaluated to seek low energy footprint products. The amount of CO_2 emission is significantly reduced from 1.12 kg CO_2 when the cutting speed is 30 $mmin^{-1}$ to 0.43 kg CO_2 when the cutting speed is at the highest tested. This reduction of almost 62% is a significant improvement in the environmental footprints.

4. CONCLUSIONS

With increasing use of titanium alloys for their light weight and high strength, it is essential to assess manufacturing routes in order to reduce the energy and carbon footprints of products. Relative to other common engineering materials the carbon footprint for extracting titanium alloys is already very high, thus effort should be put in cleaner methods of shaping the alloy. The energy consumed in machining can be used as an indirect measure of energy derived carbon footprints for a process. This is because in generating the power that is then used to drive machine tools, carbon dioxide is emitted to the atmosphere. Thus in the interest of energy availability, reducing energy costs and carbon footprints it is essential to run production operation at the lowest energy footprint (consumption) to promote a cleaner and more sustainable manufacturing industry.

- Keeping machines running while not cutting not only contributes to production waste but significantly increases the energy and carbon footprints of machine shops and machined products.
- It follows that production planning, process planning and machine loading are essential targets to be optimised in reducing environmental footprints of a machine shop.
- In designing or selecting a machine tool the functionality and loading of the spindle is a major factor in addressing power consumption.
- Comparing different machining conditions, improving the material removal rate has a very positive influence on reducing the energy/carbon footprints of a product.
- Thus high speed machining not only reduces cycle times but can be a key strategy for sustainable machining facilities.
- Design of machines with low energy consuming modules has the highest impact in reducing energy and carbon footprint from machining operations. Machines should be designed to utilise less energy and also to have a higher percentage of energy dedicated to actual material removal activity.

REFERENCES

[1] Cambridge Engineering Selector (CES)., Granta Design Limited, 2005.

[2] Carbon Trust Methodologies., DEFRA Guidelines for measuring and reporting of emissions in the UK emissions trading scheme. 2003. http://www.carbontrust.co.uk/resource/measuring_co2/Measuring_CO2_Methodologies.htm?print=1.

[3] DAHMUS J., GUTOWSKI T., *An Environmental Analysis of Machining*. Paper presented at the 2004 ASME International Mechanical Engineering Congress (IMECE) and R&D Expo, Anaheim, California.

[4] Guidelines to DEFRA's GHG Conversion Factors for Company Reporting. 2007. http://www.defra.gov.uk/environment/business/envrp/pdf/conversion-factors.pdf.

[5] GUTOWSKI T., *Design and manufacturing for the environment*: Springer-Verlag. 2007.

[6] GUTOWSKI T., DAHMUS J., THIRIEZ A., *Electrical Energy Requirements for Manufacturing Processes.* The 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium, 2006.

[7] JAFFERY S. I., MATIVENGA P. T., Assessment of the Machinability of Ti-6Al-4V alloy using the wear map approach. *International Journal Advanced Manufacturing Technology*, 2008.

[8] JESWIET J., KARA S., Carbon emissions and CES in manufacturing. *CIRP Annals - Manufacturing Technology, 57*, 2008, 17 - 20.

[9] KALPAKJIAN S., SCHMID S. R., *Manufacturing Engineering and Technology* (Vol. 5). Singapore: Pearson Prentice Hall, 2006.

[10] KARDONOWY., DAVID, N., *A Power Assessment of Machining Tools.* Massachusetts Institute of Technology, 2002.

[11] Kyoto Protocol. (1997). http://unfccc.int/kyoto_protocol/items/2830.php.

[12] RAJEMI M. F., MATIVENGA P. T., Machinability Analysis from Energy Footprint Considerations. *Journal of Machine Engineering, 8*(2), 2008, 106 - 113.

[13] STERN REVIEW., The Economic of Climate Change. 2006. http://www.hmtreasury.gov.uk/media/4/3/Executive_Summary.pdf.